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AERONAUTICAL RESEARCH COUNCIL

Some Experiments on the Heat Transfer from a Gas Flowing through a Convergent-divergent Nozzle.

- By -

O. A. Saunders* and P. H. Calder**

5th January, 1952

SUMMARY

Heat transfer at high subsonic and supersonic speeds is more complicated than at normal velocities because the cross-sectional temperature distribution is not usually fully developed. The central core of gas is often unaffected by the heat added, in contrast to one dimensional flow calculations which assume the heat to be spread over the whole cross section. Experiments are described using a water cooled convergent divergent nozzle of smooth continuous profile through which hot gases at 865°C were passed and the heat transfer measured at different positions along the divergent portion, at Mach numbers up to 1.75. The results are very consistent when plotted in terms of the length Reynolds number measured from the throat. Velocity traverses at the exit also confirm that the boundary layer may be assumed to be turbulent and to commence at the throat. The heat transfer results also agree very well with the formulae for turbulent flow over a flat plate at low speeds, suggesting that such low speed formulae may be used for supersonic flow in nozzles. Some tests with a straight pipe at high subsonic speeds give results somewhat higher than the flat plate formula, due probably to pipe radius effects.

1. THE PROCESS OF HEAT TRANSFER

The transfer of heat to a gas flowing through a duct at high subsonic or supersonic speed is more complicated than at normal velocities process because the temperature distribution across the duct seldom becomes fully developed. For example, with low speed flow in a straight pipe, except for entrance effects occurring in the first few diameters, the cross-sectional velocity and temperature distributions have reached their equilibrium forms, and the heat communicated from the walls between any two cross sections is distributed throughout the gas. In most cases of supersonic flow, on the other hand, the heat from the walls penetrates only a short distance while the gas flowing along the axis of the duct receives no heat whatever. In fact, the central core is usually unaffected by the heat added, or by the wall friction, except insofar as its cross section for flow is reduced as the boundary layer thickens. Eventually of course, with increased distance along the tube, the boundary layer must reach the axis, but before this happens the central core will have had its velocity reduced by the convergence of its boundaries and will usually no longer be supersonic. The heat is therefore

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mostly conveyed to gas in the boundary layer moving at lower speeds, and the term 'supersonic heat transfer' is somewhat misleading. The conditions assumed in the usual 'one dimensional flow' calculations of the effects of addition of heat and friction to a supersonic stream are therefore far from being fulfilled in practice.

For a divergent duct of sufficiently wide angle, the cross-section of the central core increases despite the thickening of the boundary layer and the Mach number increases accordingly, but the heat from the walls never reaches the fluid flowing along the axis.

It therefore seems meaningless to attempt to correlate 'supersonic' heat transfer with low speed results by using the diameter Reynolds number, which is characteristic of fully developed local flow. The heat transfer, in the form of the Nusselt or Stanton number, should be a function of the length Reynolds number measured from the start of the boundary layer. If the temperature and velocity boundary layers start at different positions there will be two such Reynolds numbers. The heat transfer may possibly depend also on the initial Mach number and upon the geometrical form of the passage. In the case of a convergent-divergent nozzle operating above the critical pressure ratio, assuming both boundary layers to commence at the throat, the Stanton number at any position in the divergent section can only depend upon the length Reynolds number measured from the throat and the geometrical shape of the divergent section. This will not be true, of course, if the back pressure is such as to cause shock waves, in which case the ratio of back pressure to throat pressure is a further parameter to be taken into account.

2. MEASUREMENTS OF SUPERSONIC HEAT TRANSFER

Clearly any measurements of supersonic heat transfer must be carefully related to the position in the duct at which the addition of heat begins. Previous investigations have been made by Kaye, Keenan and McAdams[1] (1949) and by Johnson and Monaghan[4] (1949). The former used a constant diameter pipe fed from a convergent-divergent nozzle, and obtained very widely scattered results which they attributed to transition effects in the boundary layer; difficulties were experienced in getting a smooth joint between the entry duct and the tube. Johnson and Monaghan started out with the idea of using a very thin sharp edged flat plate inserted in a supersonic stream, but found this impracticable owing to the difficulty in constructing a suitable heater inside the plate, and finally worked with the heated flat plate inserted in the wall of a supersonic tunnel. They attempted to start a new boundary layer at the upstream edge of the plate by sucking away the entry boundary layer through a slot just ahead of the plate. This was reasonably successful and they obtained results in quite good agreement with low velocity formulae for flat plate heat transfer. The present investigations were started in 1948 in order to obtain as accurately as possible a measurement of supersonic heat transfer up to a Mach number of 1.75 with as little uncertainty as possible about the smoothness of the surface at the point where the fluid first meets the heated surface. For this purpose it was decided to use a complete convergent-divergent nozzle, divided into sections longitudinally for the purpose of separate heat flow measurements, but getting as nearly as possible perfect fits between the sections by boring out a taper hole and reaming the taper hole with all the sections bolted up so as to get a smooth continuous profile.

The/

The use of an actual nozzle is also of direct practical interest on account of its common use. It was also decided to use hot combustion gases at some 865°C and to water cool the nozzle. This avoided moisture condensation troubles which occur when atmospheric air is employed and provided a much simpler method of supplying and removing the heat than is the case when the experiment is done by electrically heating a tube through which cold air is passed. Also the use of fairly large temperature differences between the gas and the walls enabled more accurate measurement of the temperature difference, although it introduced a slight uncertainty in the values assumed for the viscosity of the gas when calculating the Reynolds number.

3. DESCRIPTION OF APPARATUS

Fig.1 shows the general layout of the apparatus. Air from a compressor was passed through a venturi, A, for flow measurement and entered a specially designed combustion chamber, B, in which kerosene was burnt to raise the final temperature to about 865°C. The gases then passed through an approach duct, C, and finally entered the nozzle, D, from which they passed into an exhaust duct, F. The temperature of the gases was measured just before entering the nozzle by means of the suction thermocouple, F. The static pressure was measured in the approach duct.

The divergent section of the nozzle was built up in four parts bolted together through flanges, one on each section, the bolts being staggered so as to pull together each pair of adjacent flanges.

The nozzle could be operated with one, two, three or four sections in position, the exhaust section, which was water cooled and refractory lined in a similar way to the approach duct, being arranged to slide axially to accommodate different lengths of nozzle. The exhaust section also carried a traversing thermocouple and Pitot tube by which distributions of temperature and velocity at the nozzle exit could be determined.

The heat transfer to each nozzle section was deduced by measuring the temperature in the metal at two different depths, half an inch apart, the thermal conductivity of the metal having been specially measured. Sideways transfer of heat between different sections was prevented by an air gap 0.075" wide narrowing to 0.006" at the bore of the nozzle. The nozzle was kept cool by narrow axial water passages drilled in each section. It was not found practical to measure the heat transfer by means of the rise of temperature of the cooling water through each section owing to the possibility of the water in one section picking up heat by conduction through the metal from the next section. Also to obtain a reasonable water temperature rise, low velocities of the order of 4 ft/sec. would be necessary and the flow thus would be laminar and tend to cause errors in temperature measurement owing to lack of mixing. A rough overall check of the heat transfer to the whole nozzle could however be made. It was also obviously impossible to deduce the heat transfer by measuring the temperature of the gas at different points along the nozzle passage since this would have involved interfering with the supersonic flow.

4. FURTHER DETAILS OF APPARATUS

The Combustion System

The combustion system (Fig.2) consisted of an upstream injection swirling conical spray by which the fuel was thrown into an annular vortex generated by the air entering through inclined holes into the flame tube.

Spill/

Spill control burners were used for good atomisation and extra water cooling over the rear end of the burner head was found to be necessary. Since the air flow was only from 0.01 - 0.15 lbs/sec., the combustion chamber was much smaller than any conventional designs and had to be specially developed.

The Nozzle

The four sections of the nozzle were each bored out to a taper hole, the throat of the nozzle being approximately half way along the first section. The smooth profile was obtained by reaming with a long taper pin reamer with all the sections bolted up. The last section was spiggoted into a syndano bush which was sealed into the exhaust section thus providing thermal insulation from the exhaust section. Similarly the approach entry piece was insulated from the wall by a disc of syndano and water prevented from coming into contact with the mounting with a split piece of syndano, the inside of which had the same shape as the nozzle entry. The nozzle was provided with twelve static pressure holes and each section had six thermocouples, three at each depth. All the pressure and thermocouple connections were brought out through the ring of water cooling holes by means of radial drilling at points where 3 of the 60 equally spaced water holes had been left undrilled. To overcome the difficulty of drilling the 0.031" diameter static pressure holes to such a great depth from the outside, inserts were used so that the holes could be drilled from the inside ends of the inserts to break into the 0.0625" diameter holes drilled from the other end. The inserts were fitted before the main gas passage was bored out so as to obtain a flush fit.

The water seals between the nozzle sections to prevent the cooling water from leaking either into the air gaps between the sections or to the outside of the nozzle, were arranged so that metal to metal contact was always obtained between adjacent nozzle sections. Sealing rings of outsize thickness were fitted initially and were reduced to size by successive baking and reassembly in a furnace before the final reaming was carried out. The material used was Silastic, a rubber like substance which retains its resilience at high temperatures.

Thermocouples

The final design of thermocouple for measurement of nozzle metal temperature is shown in Fig.3. The two ends of the 0.013" nickel-chrome and constanton wires were pressed separately into contact with the flat bottom of the hole drilled in the nozzle by means of a thin metal disc and a spring loaded syndano cylinder. In this way good contact was obtained and the thermjunction was located precisely at the bottom of the hole. The thermocouple for measuring exhaust gas temperature consisted of a stainless steel hypodermic tube, tip welded to alumel wire 0.004" diameter passing down the tube and insulated by small quartz tubes. A suction thermocouple was also used as a check test for absolute gas temperature measurement.

5. CALCULATION OF RESULTS

The heat transfer to each section was obtained directly from the measured temperature gradient in the nozzle wall and the normal logarithmic conduction formula, and was based on the internal surface area of the hole in each section.

It/

It has now been fairly well established experimentally and theoretically that the heat transfer for high speed flow is proportional to the difference between the actual wall temperature T_W and the adiabatic wall temperature T_{Wa}, as given by the expression for the recovery factor $r = \dfrac{T_{Wa} - T}{T_0 - T}$ where T_0 is the total temperature of the gas stream, T its true temperature, and r is about 0.88. In the present experiments, owing to the big temperature difference between the wall and fluid, little error is introduced by taking T_0 instead of T_{Wa}. The wall temperature T_W was deduced by extrapolating from the measured nozzle wall temperatures. The Stanton number H/K_pG was thus calculated, knowing the total mass flow and the cross sectional area of the hole, taken at the mid-point of each section.

The Reynolds number GL/μ was also calculated from the known mass flow per unit area at the mid point of each section, the viscosity being taken at the total temperature of the stream. The variation of G along the length of the nozzle accounted for approximately 40% change in the Reynolds number between the first and last section, as compared with 600% change due to the variation of L.

6. RESULTS

Fig.4 shows the measured static pressure at different positions along the nozzle. The total pressure and total temperature of the central core of gas were assumed constant, at their measured upstream values, and hence the values of P_0/P and M given in the figure were deduced by the usual isentropic one dimensional flow formulae, using the appropriate values of γ for the combustion gases. The results in Fig.4 are, however, not used in the calculation and correlation of the heat transfer results, and are needed only in order to show the variation in Mach number along the nozzle.

Table 1 gives the heat transfer results, which have been plotted in Fig.5 using the Reynolds number based on the distance, L, from the throat. The agreement between the results for the four sections is remarkably good, and appears to show that the boundary layer may be assumed to begin approximately at the throat, as was also inferred from velocity traverses mentioned later.

It is also seen from Fig.5 that the results fit almost perfectly with the formula $St = \dfrac{0.0285}{Re^{1/5}}$, for low velocity flow past a flat plate with the boundary layer turbulent ref.5. It is therefore concluded that for the divergent nozzle used in the experiments the heat transfer is the same as for low speed flow over a flat surface with the boundary layer turbulent and starting at the throat.

In Fig.5 the temperature difference between wall and fluid has been based on the stream total temperature, assumed constant along the nozzle and equal to the upstream temperature before entry to the convergent section. For comparison purposes, the same results have been plotted in Fig.6 assuming the stream total temperature to fall along the nozzle length owing to heat removed, in accordance with the usual one-dimensional flow method of calculation. It will be seen that the correlation is distinctly less good than in Fig.5.

Velocity/

Velocity and Temperature Traverses

Fig.8 shows the distribution of velocity and temperature at the end of the last section, as measured by traversing Pitot tube and thermocouple. As would be expected for a gas, the velocity and temperature distributions are the same, the thickness of the boundary layer being about 0.120 inches. Calculation using the formula

$$\delta = \frac{0.37L}{Re^{1/5}}$$

for a turbulent flat plate boundary layer, gives 0.126 inches, which represents very good agreement, and again confirms the assumption that the turbulent boundary layer may be taken as starting approximately at the throat. The error caused by neglecting the thickness (0.009") of the laminar layer at the point of transition is small.

It is realised that the use of flat plate formula for heat transfer and boundary layer growth for a circular pipe is not strictly correct. It would be possible to use the boundary layer equations to make calculations for the actual divergent nozzle used, but preliminary investigations show that the departure from flat plate conditions is within the limits of experimental error. For a nozzle of smaller angle of divergence, or for a straight pipe, however, the error may be appreciable, as shown by Latzko[6]. Under the conditions of the Kaye, Keenan and McAdams experiments, for example, the effects of the pipe diameter may not be negligible.

Subsonic Heat Transfer

Some experiments with a straight pipe in place of the divergent section of the nozzle were also carried out, the straight section being divided into four equal lengths and the same technique used as with the divergent nozzle. The results are shown in Table 2 and Fig.7, and are of course all for subsonic speeds. The points for the sections nearest the throat agree closely with the flat plate low speed formula, but there is a progressive deviation for the positions further along the nozzle. The probable explanation is the acceleration of the core of fluid caused by the thickening boundary layer.

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NOMENCLATURE/

NOMENCLATURE

δ	Boundary layer thickness
G	Mass flow per unit area
H	Heat transfer coefficient, C.H.U./hr.ft^2 °C.
K_p	Specific heat at constant pressure
L	Length, measured from nozzle throat
M	Mach number
P	Static pressure
P_o	Total pressure
q	Conduction heat flow in nozzle section. (C.H.U./Sec.)
r	Recovery factor
Re_L	Reynolds number, GL/μ
St	Stanton number, H/K_pG
T_o	Total temperature, °C
T_w	Wall temperature, °C
T_{wa}	Adiabatic wall temperature, °C
T	Static temperature of gas, °C
μ	Viscosity

TABLE 1./

TABLE 1

SUPERSONIC HEAT TRANSFER RESULTS

Gas total temperature, T_o, constant at 865°C

Run No.	Sect. No.	q	T_W	H	Nu	St	$Re_L \times 10^{-4}$
1	1	0.583	205	343	248	0.00256	20.9
	2	0.443	160	230	179	0.00195	56.5
	3	0.403	142	192	161	0.00185	83.4
	4	0.364	127	159	144	0.00173	105.0
2	1	0.526	189	302	218	0.00255	18.5
	2	0.400	147	204	159	0.00195	49.8
	3	0.380	135	179	151	0.00195	73.8
	4	0.331	117	143	130	0.00175	92.8
3	1	0.484	176	273	198	0.00265	16.2
	2	0.384	142	195	153	0.00214	43.5
	3	0.356	127	166	140	0.00208	64.4
	4	0.304	109	130	119	0.00184	81.3
4	1	0.443	162	245	177	0.00265	14.4
	2	0.345	129	172	135	0.00211	38.9
	3	0.297	111	135	114	0.00190	57.7
	4	0.281	100	119	109	0.00188	72.7
5	1	0.405	151	220	159	0.00262	13.2
	2	0.323	121	159	124	0.00215	35.5
	3	0.295	108	134	113	0.00206	52.5
	4	0.263	95	110	101	0.00192	66.2
6	1	0.386	144	208	151	0.00274	11.9
	2	0.294	113	143	112	0.00226	30.3
	3	0.271	101	122	104	0.00220	45.0
	4	0.249	91	104	96	0.00211	56.8
7	1	0.333	128	176	128	0.00270	10.1
	2	0.268	104	129	101	0.00225	27.4
	3	0.249	94	111	94	0.00221	40.8
	4	0.227	85	94	87	0.00211	51.4
8	1	0.318	122	166	121	0.00284	9.2
	2	0.257	101	123	97	0.00238	24.8
	3	0.235	90	104	89	0.00230	36.9
	4	0.224	84	93	86	0.00231	46.6
9	1	0.538	198	313	225	0.00210	23.2
	2	0.459	168	241	187	0.00183	62.3
	3	0.414	149	199	166	0.00172	92.5
	4	0.382	135	169	152	0.00166	115.0
10	1	0.635	222	384	276	0.00233	25.7
	2	0.478	173	253	196	0.00173	69.1
	3	0.455	158	221	184	0.00173	102.0
	4	0.427	148	193	174	0.00169	128.8

TABLE 2./

TABLE 2

SUBSONIC HEAT TRANSFER RESULTS

Run No.	Sect. No.	q	$T_o - T_W$	H	Nu	St	$Re_L \times 10^{-4}$
11	1	0.410	716	223	161	0.00263	13.2
	2	0.359	730	191	137	0.00226	39.6
	3	0.346	735	183	132	0.00216	66.0
	4	0.323	743	169	122	0.00200	92.4
12	1	0.350	744	183	131	0.00279	10.1
	2	0.310	755	160	115	0.00244	30.4
	3	0.302	758	155	111	0.00236	50.7
	4	0.294	762	150	107	0.00229	71.0
13	1	0.289	762	147	106	0.00290	8.0
	2	0.257	771	129	93	0.00255	23.7
	3	0.249	774	125	90	0.00246	39.6
	4	0.235	779	117	84	0.00230	55.4
14	1	0.210	771	106	77	0.00266	6.3
	2	0.210	771	106	77	0.00266	18.9
	3	0.210	772	106	77	0.00266	31.4
	4	0.203	774	102	74	0.00256	44.0
15	1	0.223	815	106	75	0.00305	5.3
	2	0.199	822	94	66	0.00270	16.0
	3	0.195	824	92	65	0.00264	26.6
	4	0.195	825	92	65	0.00264	37.3

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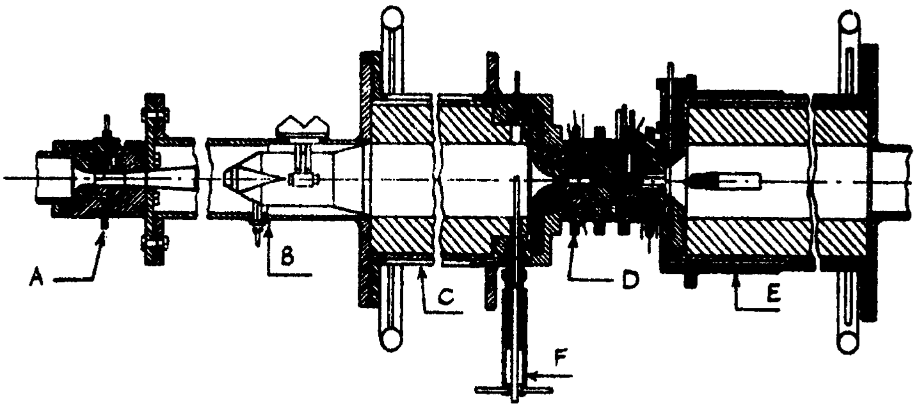
FIGS. 1 & 2.

FIG. 1.



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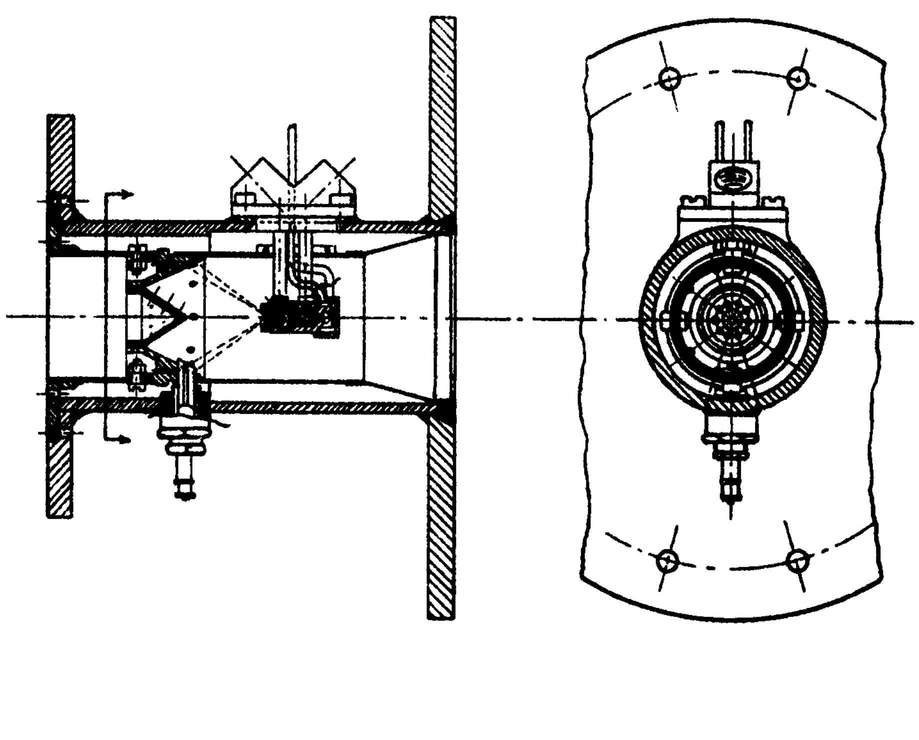

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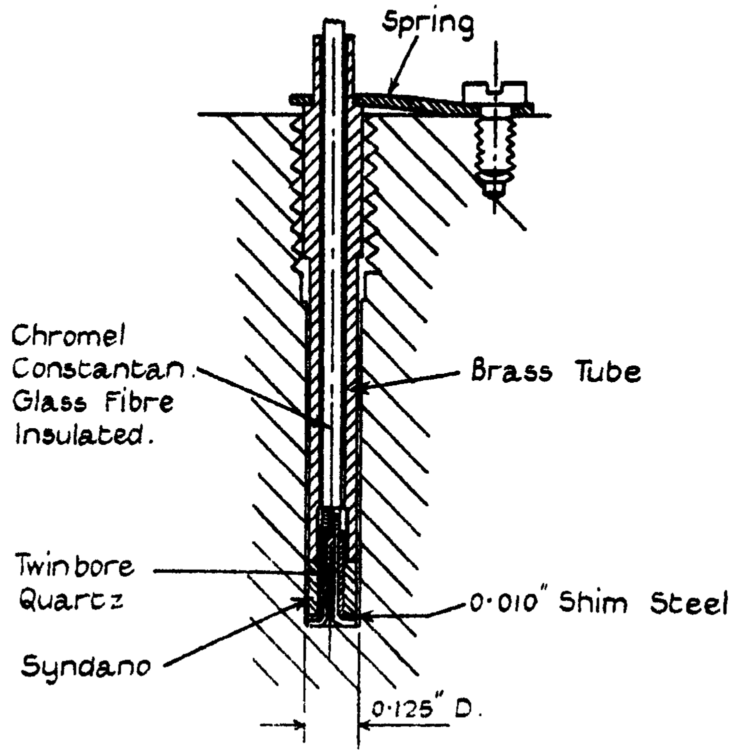

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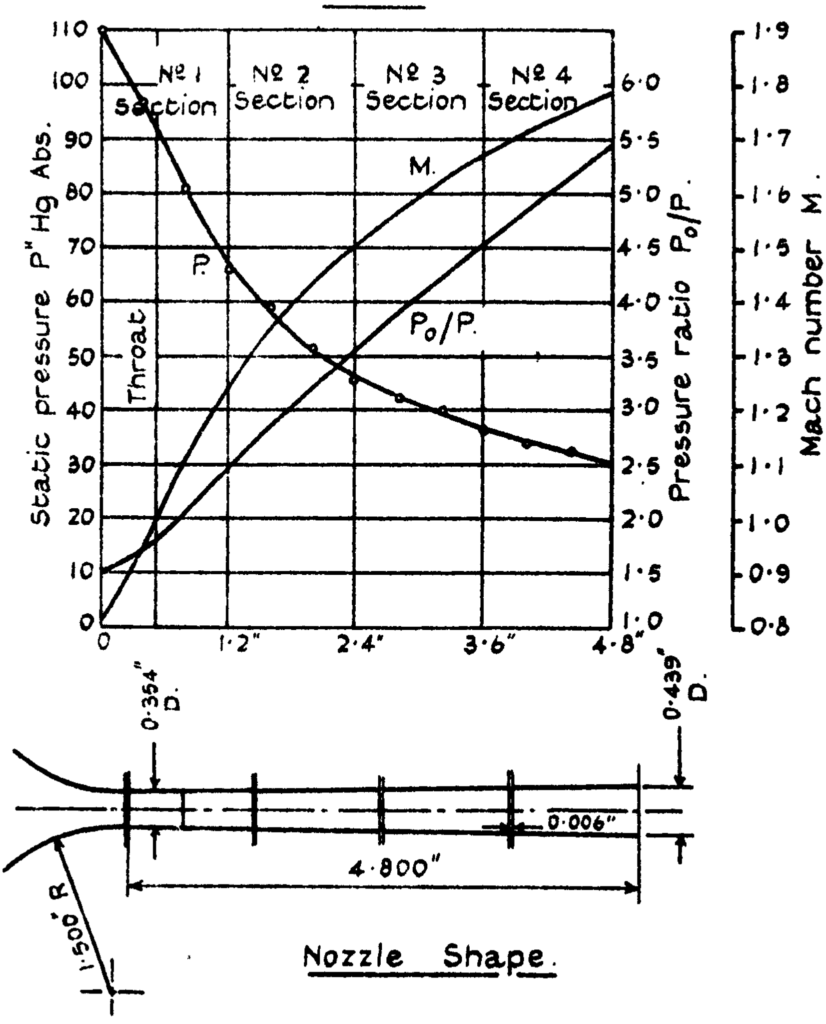
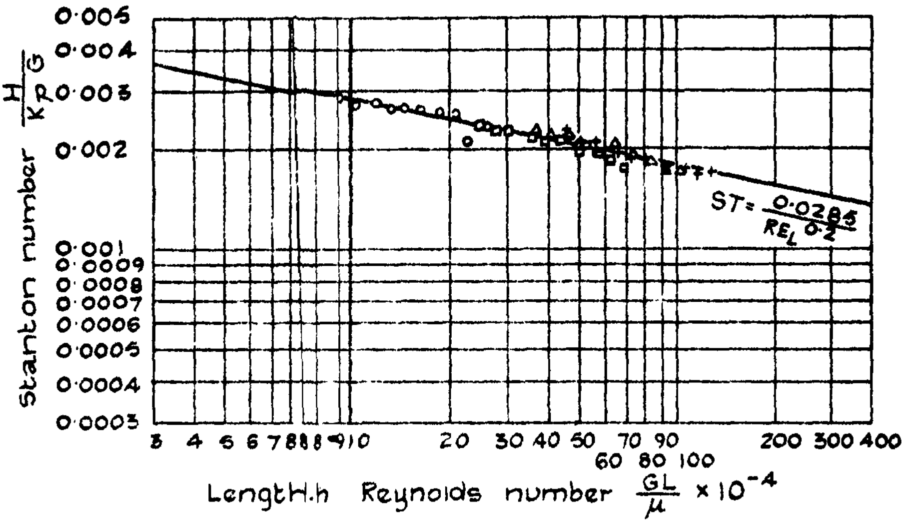


Nozzle Shape.

FIG. 5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$ST = \frac{0·0285}{RE_L^{0·2}}$
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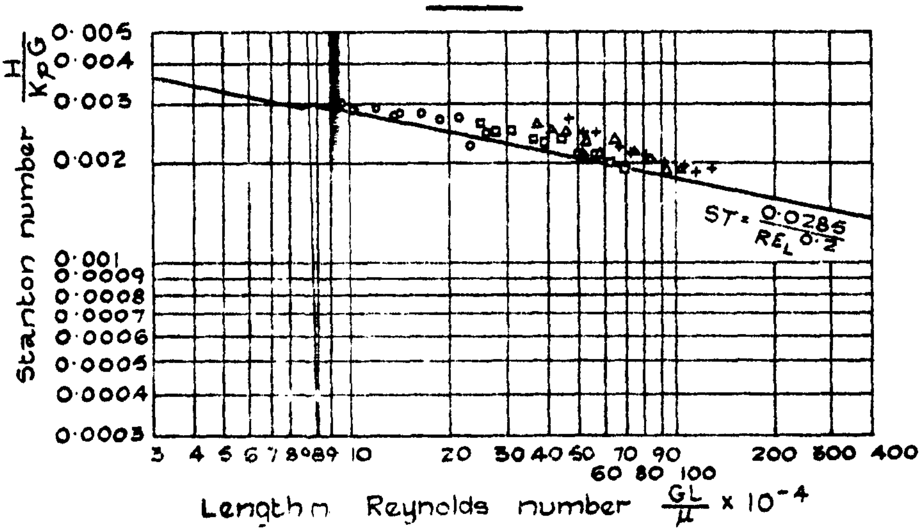
Length Reynolds number $\frac{GL}{\mu} \times 10^{-4}$

FIG. 6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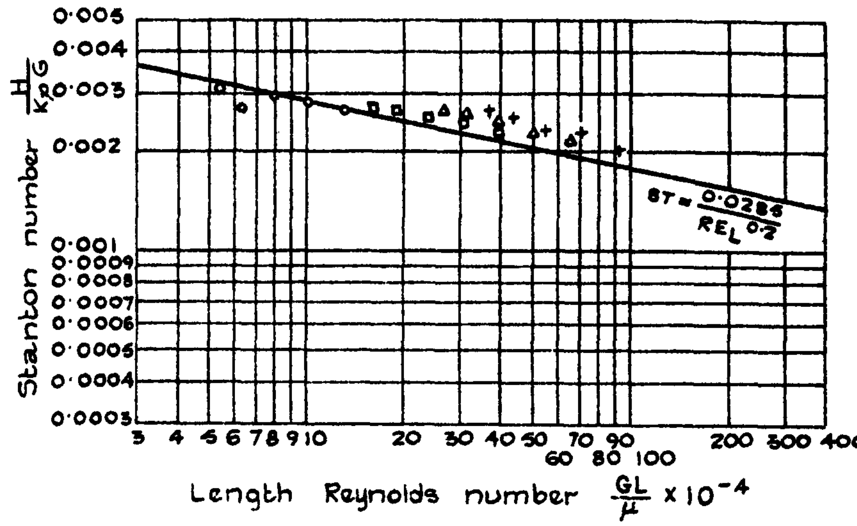
Length Reynolds number $\frac{GL}{\mu} \times 10^{-4}$

Fig. 7.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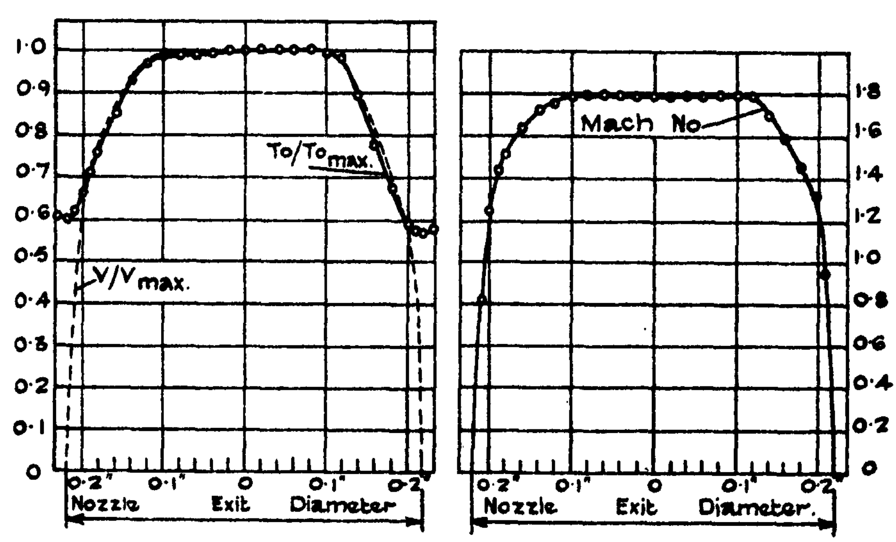
Length Reynolds number $\frac{GL}{\mu} \times 10^{-4}$
$ST = \frac{0.0286}{RE_L^{0.2}}$

Fig. 8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Nozzle Exit Diameter.

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